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ORIGINAL PAPER

Assessment of soil erodibility and aggregate stability for different parts of a forest road

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Abstract: We measured erodibility and mean weight diameter (MWD) of soil aggregates in different parts of a forest road. Samples of topsoil were collected from cutslope, fillslope, road surface and forest ground to assess the texture, bulk density, moisture, $CaCO_3$ and organic matter. Soil aggregate stability was determined by wet sieving. Soil erodibility on the road surface was 2.3 and 1.3 times higher than on the fillslope and cutslope, respectively. The forest soil had the lowest erodibility. Aggregate stability of cutslope and road surface were low and very low, respectively. There was a significant negative relationship between cutslope erodibility with $CaCO_3$ and sand content. Cutslope erodibility increased with increasing silt, clay and moisture content. On fillslopes, MWD increased with increasing rock fragment cover, plant cover, litter cover, organic matter and sand. There was a strong negative correlation between fillslope erodibility and organic matter, sand and MWD. There was no significant difference between erodibility of bare soil and soils beneath *Rubus hyrcanus* L. and *Philonotis marchica* (Hedw.) Brid.

Keywords: road prism, soil erodibility, aggregate stability, wet sieving, Lat Talar forest

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Introduction

Mountain roads are the most prodigious source of sediment because of low stability of road aggregates and high erodibility in some part of its prisms (Sidle et al. 2011). Aggregate stability of a soil is the resistance of soil structure against mechanical or physical-chemical destructive forces. Determining aggregate stability will give information on the sensitivity of soils to water and wind erosion, which might be prevented by revegetation (Mandy et al. 2009). Revegetation of the road cutslopes and fillslopes increases soil aggregate stability by accelerating vegetation development and by promoting soil formation processes such as accumulation of fine soil particles, organic matter and mycorrhizal propagules (Burri et al. 2009).

Aggregates can form by the breakdown of consolidated soil mass into smaller sizes (Dvorak and Novak 1994). Soil aggregate stability and size distribution vary widely over time and space (Kusky 2008). Aggregate density affects soil erodibility to a lesser extent but is much less variable than stability and size distribution (Morgan 2005). Soil erodibility factors quantify the susceptibility of soil detachment by water. These erodibility factors predict the long-term average soil loss (Bryan 2000; Mbagwu 2003).

Road prisms including cutslopes, road surfaces and fillslopes can be important contributors of sediment to streams in forested watersheds. The road surface is the compacted area used to support traffic. The cutslope is created by excavation into the natural hillslope, and it is steeper than the natural slope. The lack of aggregate stability directly affects surface erosion rates in unprotected soils of cutslopes (Clayton 1983). Fillslope is an unconsolidated excavated material pushed to the slope below the road; it is also steeper than the natural slope (Jordán-López et al. 2009). Previous works suggested that cutslopes are a significant source of sediment and possibly the primary sites of erosion as a result of logging operations (Megahan 1978; Riley 1988). Jordán and Martínez-Zavala (2008) reported that the soil loss from the

cutslope was 5 and 6 times higher than from the roadbed and the fillslopes, respectively. Simulation experiments have shown that the sediment load varies considerably for various conditions with cut-and-fill slopes contributing greatly to the total sediment load of the road prism.

In north Iran, roads are generally the dominant source of sediment in forest basins, but information about erodibility of forest road prisms and its relationship with other environmental factors is very limited. The objectives of this research were to (1) compare the soil erodibility and aggregate stability of the different parts of a forest road prism, (2) determine the effects of some environmental parameters on road erodibility and aggregate stability and (3) identify aggregate stability of the soil beneath two types of vegetation cover on cutslope.

Materials and methods

study area

Lat Talar forest within watershed number 71 in Hyrcanian zone of Iran was selected as the study area. The location of the research area was at latitude 53°9□40□ to 53°13□55□ N and longitude 36°12□55□ to 36°15□45□ E. The region has a very moist to mid moist and cold climate with a mean annual precipitation of 800 mm. The bedrock is typically marl, marl lime and limestone with a soil texture of loam and clay loam. Forest stands were dominated by *Fagus orientalis* Lipsky, *Carpinus betulus* and herbaceous species including *Carex silvatica*, *Buxus hyrcanus, Berachypodium silvaticum*, *Ruscus hyrcanu*s, *Phyllitis scolopendrium, Rubus hyrcanus L.* and *Polypodium auidinum*. Forest roads in the studied area were used by truck, motorcycle and cars. The traffic density was 5 vehicles per day. Mean litter thickness on fillslope and forest ground was 2 cm and on cutslope and road surface was 0.1 cm. *Philonotis marchica* (Hedw.) Brid. (also known as philonotis moss) is of the Bartramiaceae family and grows in calcareous wetlands in North, West and Central Europe, West Asia, Japan, Korea, North America, Algeria, Madeira (Šoltés 2008). *Rubus* is a large genus of flowering plants of the rose family, Rosaceae. Most of these plants have woody stems and are frequency found at the margin of Hyrcanian forest roads (Hosseini et al. 2011).

Determination of plant and litter cover

Plant and litter cover were determined by taking a digital picture of every sampling plot on the different parts of forest road. Then, the percentage of plant and litter cover was calculated using a grid with cells of 0.25 cm^2 in Fishnet extension in Arc GIS.

Determination of chemical and physical parameters of soil

In total, 25 samples of topsoil (0–20 cm deep) were randomly collected from five types of site in the road prism and adjacent forest, cutslope, fillslope, road surface, forest ground and soil beneath *Philonotis marchica* and *Rubus hyrcanus* by cylinder (484 cm^3) for physical (soil texture, bulk density and moisture) and chemical analysis (T.N.V or $CaCO_3$ and organic matter). Soil texture was determined by the Bouyoucos hydrometer method. Lime percentage (T.N.V or $CaCO_3$) was measured by the NaOH titration method. Soil organic carbon was determined using the Walkley-Black technique. Slope gradient was measured using an inclinometer. Soil bulk density (*BD*) was calculated by Eq. 1:

$$BD = \frac{S_w - R_w}{C_V - R_V} \tag{1}$$

where, S_w is the total dry weight of soil (gr), R_w the dry weight of rubble and root (gr), C_V the cylinder volume (cm^3) and R_V is rubble and root volume (cm^3).

Determination of the soil erodibility index

The soil erodibility equation provides an estimate of K, which can be calculated by Eq. 2 (Wischmeier and Smith 1978). Soil particle size distribution was described according to percentage of clay (<0.002 mm), silt (0.002–0.05 mm), very fine sand (0.05–0.1 mm) and sand (0.1–2 mm):

$$K = \frac{0.00021M^{1.14}(12-OM)+3.25(C_{soilstr}-2)+2.25(Cperm-3)}{100} \tag{2}$$

where, *K* is the soil erodibility factor; *OM* is the organic matter content (%); C_{perm} is the soil permeability class which can have one of the 6-class values: 1 refers to fast, 2 from moderate to fast, 3 is moderate, 4 from slow to moderate, 5 slow and 6 very slow; $C_{soilstr}$ is the soil structure class ranging from 1 to 4 (friable is 1, fine polyhedral is 2, medium to coarse polyhedral is 3 and solid is 4). *M* is a particle size parameter and can be written as Eq. 3:

$$M = (m_{silt} + m_{vfsand})(100 - m_c) \tag{3}$$

Determination of the mean weight diameter of soil aggregate

Soil samples taken from cutslope (9 replications), fillslope (7 replications), road surface (3 replications) and forest ground (6 replications) were used in wet sieving tests. Fifty grams of soil sample with aggregate size <4.75 mm were weighed for wet sieving. Aggregates were transferred onto a series of sieves with 2, 1, 0.5, 0.425, 0.212, 0.090 and 0.045 mm openings. Sieves were placed underwater in a pail of the wet-sieving machine for 10 minutes. This machine moved the sieve up and down in the water through a vertical distance of 1.5 cm at a rate of 30 oscillations per minute. The soil aggregates remaining on the sieve were oven-dried for approximately 24 hours at 105°C. The Mean Weight Diameter (MWD) of soil aggregate was calculated using Eq. 4 (Skidmore and Layton 1992; Gee and Or 2002):

$$MWD = \sum_{i=1}^{n} x_i w_i \tag{4}$$

where, x_i is the mean diameter of aggregate remaining on the sieve; w_i is the ratio of the weight of aggregates remaining on each sieve to total weight of the sample and n is the number of sieves. The sensitivity degree of soil aggregates to instability is listed in Table 1.

Table 1. Sensitivity of soil aggregate to instability based on Mean Weight Diameter (MWD)

Sensitivity to erosion	Very high	High	Moderate	Low	None
MWD (mm)	<0.5	0.5-1	1–2	2–2.5	>2.5

Based on the classification of Karimi et al. (2008)

Statistical analysis

Soil erodibility index and aggregate stability data were statistically analyzed using the GLM procedure in SAS software. SNK test (Student Newman Kouls) was used to compare means for different parts of the road.

Results

Soil erodibility index and aggregate stability of different parts of the road

Forest soil had higher mean weight diameter than did the road prism (p =0.0027). Mean weight diameter of road surface aggregates was less than for cutslope and fillslope aggregates. Soil erodibility was significantly higher on the road surface. The forest had the lowest soil erodibility. The set of samples collected from cutslope and road surface showed low and very low aggregate stability, respectively (Table 2). Weight distribution of aggregates is defined as the weight of each aggregate size after wet sieving as a percentage of the total weight of the soil sample (50 g). Means for weight distribution of aggregate size in forest soil was highest for the higher aggregate size, while the lower aggregate size had less weight distribution. This was reversed for weight distribution of aggregate size on the road surface. The weight distribution curves of aggregate size for cutslopes and fillslopes was irregular (Fig. 1). Forest soil aggregates remaining on each sieve are shown in Fig. 2.

Table 2. MWD and K for different parts of the forest road (Mean±SE) (based on classification of Karimi et al. 2008)

Variables	Cutslope	Fillslope	Road surface	Forest	ANOVA, p
MWD (mm)	0.77^b±0.27	1.04^b±0.32	0.43^b±0.11	1.63^a±0.76	0.0027
Soil erodibility factor (K)	0.17^b±0.04	0.10^c±0.01	0.23^a±0.03	0.04^d±0.007	<0.0001
Aggregate stability	Low	Moderate	Very low	Moderate	0.0027

In a row, means with the same letter are not significantly different based on Student-Newman-Keuls Test, α=0.05.

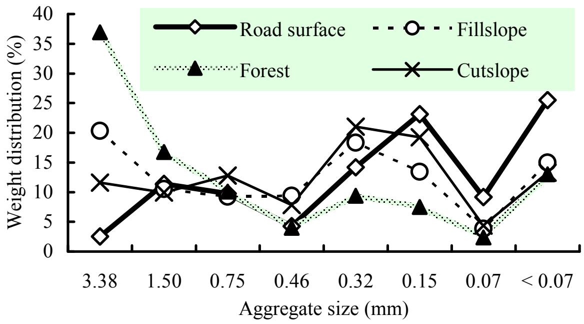

Fig. 1. Weight distribution of aggregate sizes for forest soil and the road prism

Correlation of environmental parameters, soil erodibility and aggregate stability

Table 3 lists the differences in environmental parameters for different parts of the road prism. We found a significant negative correlation between soil erodibility and the percentage of surface rock fragment cover on cutslopes. Soil bulk density decreased with increasing MWD on cutslopes. Moreover, a positive significant correlation was detected for MWD and organic matter and $CaCO_3$. MWD decreased with increasing silt content of soil. There was a significant negative relationship between cutslope erodibility and $CaCO_3$. Cutslopes erodibility increased with increasing silt, clay and moisture content of the soil (Table 4). MWD had significant negative correlation with bulk density, moisture, clay and silt content of fillslopes. Fillslope MWD increased with increasing rock fragment cover, plant cover, litter cover, organic matter and sand. There were strong negative correlations between fillslope erodibility and organic matter, sand and MWD. Moreover, fillslope erodibility decreased with decreasing soil bulk density, moisture, clay and silt (Table 5). There was a negative relationship between MWD and moisture content of forest soil, a positive relationship between MWD and $CaCO_3$. Forest soil erodibility increased significantly with decreasing plant cover, litter cover, organic matter, sand and MWD, but soil erodibility was positively correlated with measured slope gradient, moisture, bulk density, clay and silt content of forest soil (Table 6). Road surface erodibility increased with increasing silt, clay and moisture, while there was significant negative correlation between soil erodibility and organic mater, $CaCO_3$, MWD and sand content of the road surface. MWD was negatively correlated with moisture; clay and silt content (Table 7).

Erodibility of soil beneath *Rubus hyrcanus* and *Philonotis marchica*

For aggregate sizes <0.32 mm, the weight distribution of soil aggregates beneath *Rubus hyrcanus* was lower than for soil beneath *Philonotis marchica* and bare soil. For aggregate size in the range of 0.32-3.38 mm the weigh distribution of soil aggregates for *Rubus hyrcanus* was higher (Fig. 3). There was no significant difference between soil erodibility factors for bare soil, soils

beneath *Rubus hyrcanus* and *Philonotis marchica* due to the steep slope. The mean weight diameter of soil aggregate under *Rubus hyrcanus* was significantly less than for *Philonotis marchica* and bare soil (Table 8).

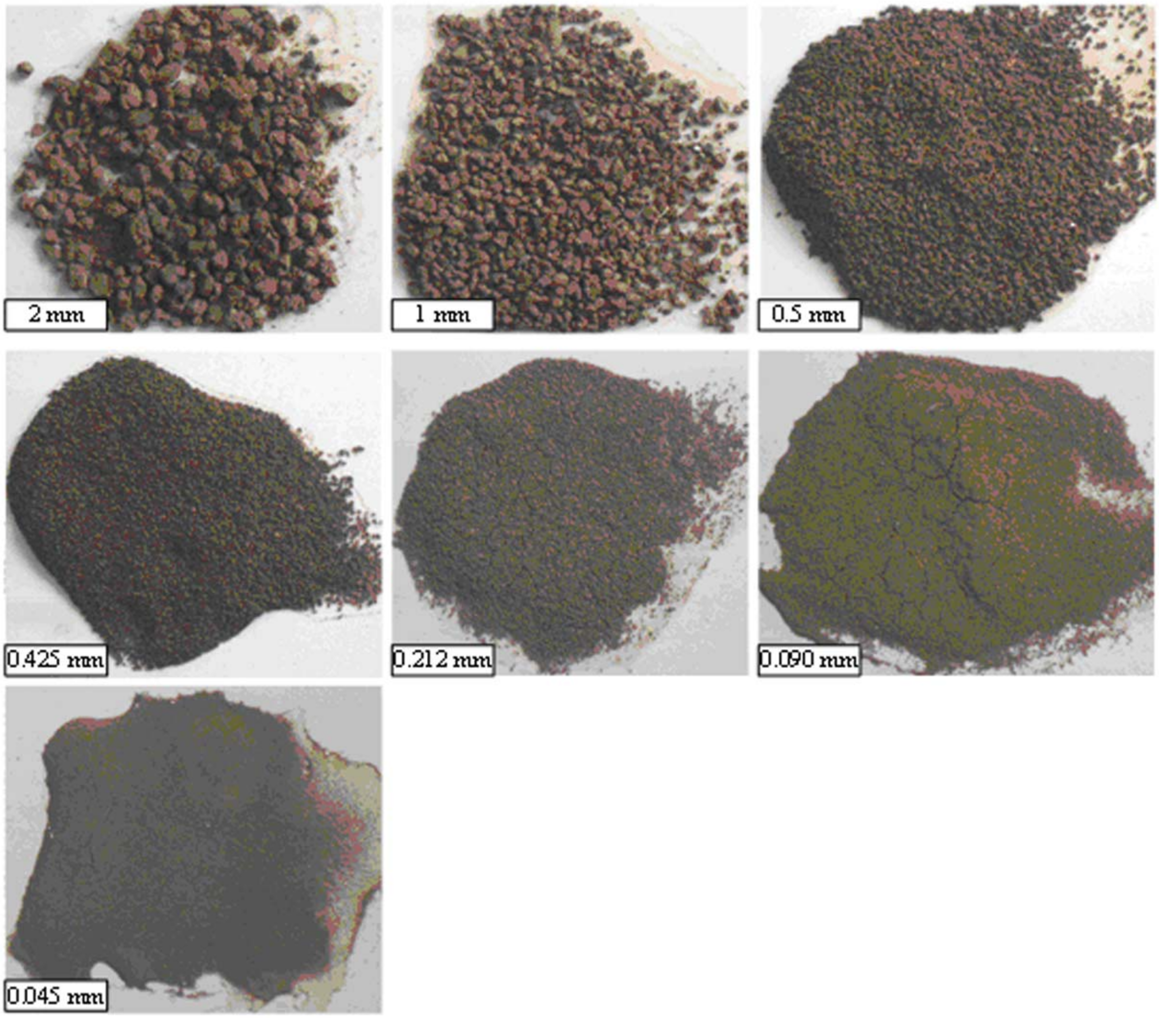

Fig. 2. Forest soil aggregates remaining on sieves of 2, 1, 0.5, 0.425, 0.212, 0.09 and 0.045 mm

Table 3. Environmental parameters for different parts of the road (Mean±SE)

Parameters	Road surface	Cutslope	Fillslope	Forest ground	ANOVA p
Slope (degree)	6.9d±0.7	47.3a±7.6	38.5b±3.0	24.7c±4.7	<0.0001
Rock fragmen cover (%)	81.9a±2.0	2.5b±1.1	2.2b±0.8	0.0c±0.0	<0.0001
Plant cover (%)	0.0b±0.0	28.7a±7.8	25.8a±8.9	4.7b±1.0	0.0003
Litter cover (%)	5.3c±1.5	15.1c±4.0	44.5b±7.2	77.7a±18.2	<0.0001
Sand (%)	65.04a±10.54	58.01a±10.29	50.43a±12.81	62.25a±8.00	0.0843
Silt (%)	15.53b±2.24	21.29ab±6.67	24.11a±5.60	19.50ab±3.13	0.0610
Clay (%)	19.43a±3.09	20.70a±7.36	25.45a±7.11	18.25a±2.70	0.1597
Organic matter (%)	0.89b±0.04	1.97b±0.55	2.22b±0.86	4.68a±1.12	0.0014
CaCO3 (%)	42.26a±0.88	26.96c±6.00	32.29b±4.59	7.26d±0.64	<0.0001
Moisture (%)	6.20c±1.03	16.24b±3.47	19.86b±2.79	26.65a±3.67	<0.0001
Temperature (°C)	21.50a±2.50	17.50ab±1.50	18.00ab±2.30	18.20ab±1.90	0.0072
Bulk density (g cm^{-3})	-	1.23b±0.15	1.40a±0.13	1.13b±0.13	0.0002

In a row, means with the same letter are not significantly different based on Student-Newman-Keuls Test, α=0.05.

Table 4. Spearman correlation coefficients for cutslopes

No.	Variable	1	2	3	4	5	6	7	8	9	10	11	12
1	Slope	1											
2	Rock fragment cover	-0.18	1										
3	Litter cover	-0.01	0.10	1									
4	Plant cover	0.51***	-0.38***	0.37**	1								
5	Bulk density	0.40***	0.22	0.10	-0.01	1							
6	Moisture	-0.11	-0.60***	-0.23	0.24*	-0.42***	1						
7	Organic matter	-0.62***	-0.30**	-0.27*	-0.41***	-0.72***	0.34**	1					
8	$CaCO_3$	-0.40***	0.55***	0.08	-0.15	0.15	-0.07	-0.17	1				
9	clay	0.52***	-0.21	0.17	0.39***	0.20	0.41***	-0.35**	-0.12	1			
10	silt	0.25*	-0.56***	0.12	0.35**	-0.13	0.53***	-0.09	-0.42***	0.50***	1		
11	sand	-0.43***	0.48***	-0.08	-0.48***	-0.07	-0.54***	0.20	0.24*	-0.83***	-0.81***	1	
12	MWD	-0.19	-0.13	-0.17	0.21	-0.37*	-0.23	0.43**	0.45**	-0.25	-0.55***	-0.22	1
13	Soil erodibility	0.28	-0.42**	-0.12	-0.15	-0.05	0.38**	0.28	-0.65***	0.40**	0.50***	-0.57***	0.07

Table 5. Spearman correlation coefficients for fillslopes

No	Variable	1	2	3	4	5	6	7	8	9	10	11	12
1	Slope	1											
2	Rock fragment cover	0.13	1										
3	Litter cover	-0.33**	0.33**	1									
4	Plant cover	0.54***	-0.13	0.02	1								
5	Bulk density	0.01	-0.01	-0.19	0.07	1							
6	Moisture	-0.12	0.12	0.13	0.18	-0.33**	1						
7	Organic matter	-0.12	-0.16	0.19	-0.20	0.09	0.14	1					
8	$CaCO_3$	-0.39**	-0.49***	-0.19	0.11	0.16	-0.03	-0.36**	1				
9	clay	0.03	-0.20	-0.65***	0.06	0.37**	0.39**	-0.39**	0.21	1			
10	silt	0.52***	0.06	-0.23	0.24*	0.47***	0.06	0.07	-0.34**	0.11	1		
11	sand	-0.48***	-0.11	0.58***	-0.17	-0.62***	-0.22	0.35**	0.02	-0.56***	-0.76***	1	
12	MWD	-0.13	0.73***	0.50**	0.41*	-0.68***	-0.75***	0.82***	0.21	-0.43*	-0.46**	0.75***	1
13	Soil erodibility	0.07	0.29	-0.29	0.31	0.75***	0.53***	-0.75***	-0.07	0.36*	0.39*	-0.68***	-0.86***

*,**, ***: Significant at probability level of 5, 1 and 0.1%, respectively; ns: not significant

Table 6. Spearman correlation coefficients for forest

No.	Variable	1	2	3	4	5	6	7	8	9	10	11
1	Slope	1										
2	Litter cover	-0.10	1									
3	Plant cover	0.07	-0.01	1								
4	Bulk density	-0.24	-0.27	-0.69***	1							
5	Moisture	-0.39**	0.10	0.10	-0.17	1						
6	Organic matter	0.39**	0.45**	0.40**	-0.28*	0.62***	1					
7	$CaCO_3$	0.52***	0.09	-0.02	-0.19	0.07	0.35*	1				
8	clay	-0.49***	0.24	-0.58***	0.64***	0.42**	-0.80***	-0.48***	1			
9	silt	-0.33*	0.53***	-0.66***	0.52***	-0.13	-0.50***	-0.07	0.70***	1		
10	sand	0.48***	-0.34*	0.63***	-0.57***	-0.36*	0.76***	0.42**	-0.97***	-0.82***	1	
11	MWD	0.15	0.01	0.28	-0.31	-0.71***	0.20	0.71***	-0.08	-0.14	0.08	1
12	Soil erodibility	0.64***	-0.41*	-0.68***	0.43*	0.94***	-0.83***	-0.20	0.77***	0.71***	-0.77***	-0.48**

Table 7. Spearman correlation coefficients for road surface

No	Variable	1	2	3	4	5	6	7	8	9	10	11
1	Slope	1										
2	Rock fragment cover	0.47***	1									
3	Litter cover	0.10	-0.10	1								
4	Moisture	0.10	0.36**	-0.02	1							
5	Organic matter	0.08	-0.18	0.10	-0.07	1						
6	$CaCO_3$	0.08	-0.18	0.12	-0.08	0.09	1					
7	clay	0.10	0.28*	-0.15	0.93***	-0.01	-0.91***	1				
8	silt	-0.16	-0.01	0.13	0.71***	-0.02	-0.12	0.80***	1			
9	sand	0.12	-0.11	0.01	-0.84***	0.07	0.17	-0.93***	-0.96***	1		
10	MWD	0.08	-0.16	-0.01	-0.83***	0.93***	0.93***	-0.89***	-0.95***	0.98***	1	
11	Soil erodibility	0.11	0.20	0.01	0.83***	-0.92***	-0.95***	0.89***	0.94***	-0.97***	-0.91***	1

*,**, ***: Significant at probability level of 5, 1 and 0.1%, respectively; ns: not significant

Table 8. MWD, K and aggregate stability of soil under different species and maintained under bare conditions (Mean±SE) (based on classification of Karimi et al. 2008)

Variables	*Rubus hyrcanus*	*Philonotis marchica*	Bare soil	ANOVA, *p*
MWD (mm)	0.73^{b}±0.11	0.77^{a}±0.08	0.78^{a}±0.12	0.0126
Soil erodibility factor (K)	0.15^{a}±0.03	0.16^{a}±0.03	0.17^{a}±0.04	0.716
Aggregate stability	Low	Low	Low	0.0126

In a row, means with the same letter are not significantly different based on Student-Newman-Keuls Test, α=0.05.

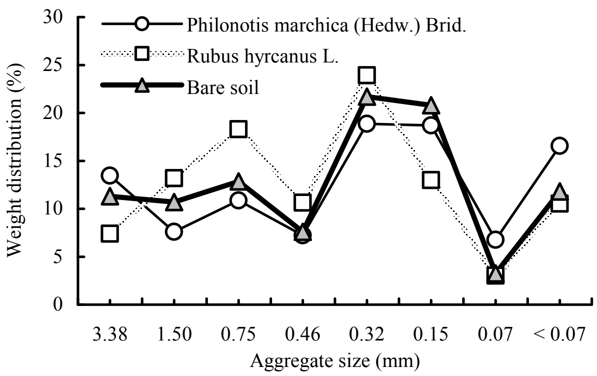

Fig. 3. Weight distribution of aggregate size in soil beneath plant species and bare soil

Discussion

We found that soil erodibility was significantly higher on the road surface than on fillslope and cutslope (Table 2). Jordán and Martínez-Zavala (2008) reported that total soil loss from the cutslope was 5 and 6 times higher than from the roadbed and fillslopes, respectively, when subjected to rainfall simulation. This report was not in agreement with our findings, because some parameters such as vegetation cover and slope gradient were not considered in the calculation of K. Soil texture is an important character contributing to soil erodibility. Soils of high content of silt and very fine sand, or expanding clay minerals tend to have high erodibility (Neyshabouri et al. 2011). We conclude that their differences in soil erodibility were affected by soil texture, since permeability and soil structure variation in their study area were low.

A significant negative correlation was found between soil erodibility and the percentage of surface rock fragment cover on cutslopes (Table 4). Jordán-López et al. (2009) demonstrated that surface rock fragment cover was negatively correlated with soil erodibility, while embedded rock fragments were positively correlated with soil erodibility. Cutslope erodibility decreased with increasing $CaCO_3$ (Table 4). $CaCO_3$ deposits among soil particles as cement and then agglutinates soil aggregates (Yadav and Girdhar 1981). Thus, $CaCO_3$ increases mean weight diameter and consequently increases aggregate stability (Nadler et al. 1996). Dispersal of clay particles in soil decreases with increasing $CaCO_3$. $CaCO_3$ improves the soil structure (Amezketa 1999). Cutslope erodibility increased with increasing silt, clay and moisture content of the soil (Table 4). Indeed soil moisture content is such a dynamic property that looking for the relations between soil erodibility, aggregate stability and moisture content could lead to misleading conclusions. It has been proven that there is no adherence among silt particles, so during rainfall they are easily separated (Refahi 2006). Pohl et al. (2011) demonstrated the positive effect of plant diversity on aggregate stability. Moreover, they found that aggregate stability increased with increasing root density and number of plant species, but when sand (<2 mm) increased, aggregate stability decreased. It has been proven that organic matter content influences soil erosion through its effect on the stability of aggregates (Guerra 1994).

Refahi (2006) reported that soil erodibility decreased linearly with increasing organic matter in the range of 0-10%. This finding was similar to our results. Organic matter leads to increased mean weight diameter and consequently causes increased aggregate stability (Monnier 1965). Organic matter generates a more active fauna and flora and, in consequence, bigger aggregates (Angers and Carter 1996; Heil and Sposito 1995). Fillslope erodibility decreased with decreasing soil bulk density, moisture, clay and silt (Table 5). Similar findings were recorded by Jordán-López et

al. (2009) and Martínez-Zavala et al. (2008). They found that soil loss on fillslopes and roadbeds was negatively correlated with sand content, but positively correlated with clay content. Forest soil erodibility increased with decreasing plant cover and increasing slope gradient (Table 6). The slope is an important factor influencing the overland flow generation and soil erosion. It has significant effect on net rain excess, overland flow depth, flow velocity and shear stress (Liu et al. 2001). Higher amounts of vegetation cover are associated with a generalized delay in runoff, an increase in soil infiltration capacity and reduction of soil erodibility (Moreno-de las Heras et al. 2009). Soil beneath *Rubus hyrcanus* showed more erosion-resistant aggregates than did soil beneath *Philonotis marchica* or bare soil. This is attributed to development of more stable soils under vegetation cover due to greater shade (Cerdá 1998).

In Iran's Hyrcanian forests, roads on hillslopes are very susceptible to water erosion. This is the result of physical features of the road prisms (steep slopes, vegetation cover and soil), climate (frost and storms), as well as traffic volumes. We conclude that soil erodibility on the road surface was 2.3 and 1.3 times higher than on the fillslope and cutslope, respectively. Forest soil had the lowest soil erodibility. Management practices such as mulching and hydroseeding can be useful to decrease soil erodibility of road prisms.

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